The Coal Combustion Process within the Basic Steam Turbine Power Plant

By: Omar El-Rouby
omar.el-rouby@mail.mcgill.ca

Terminology

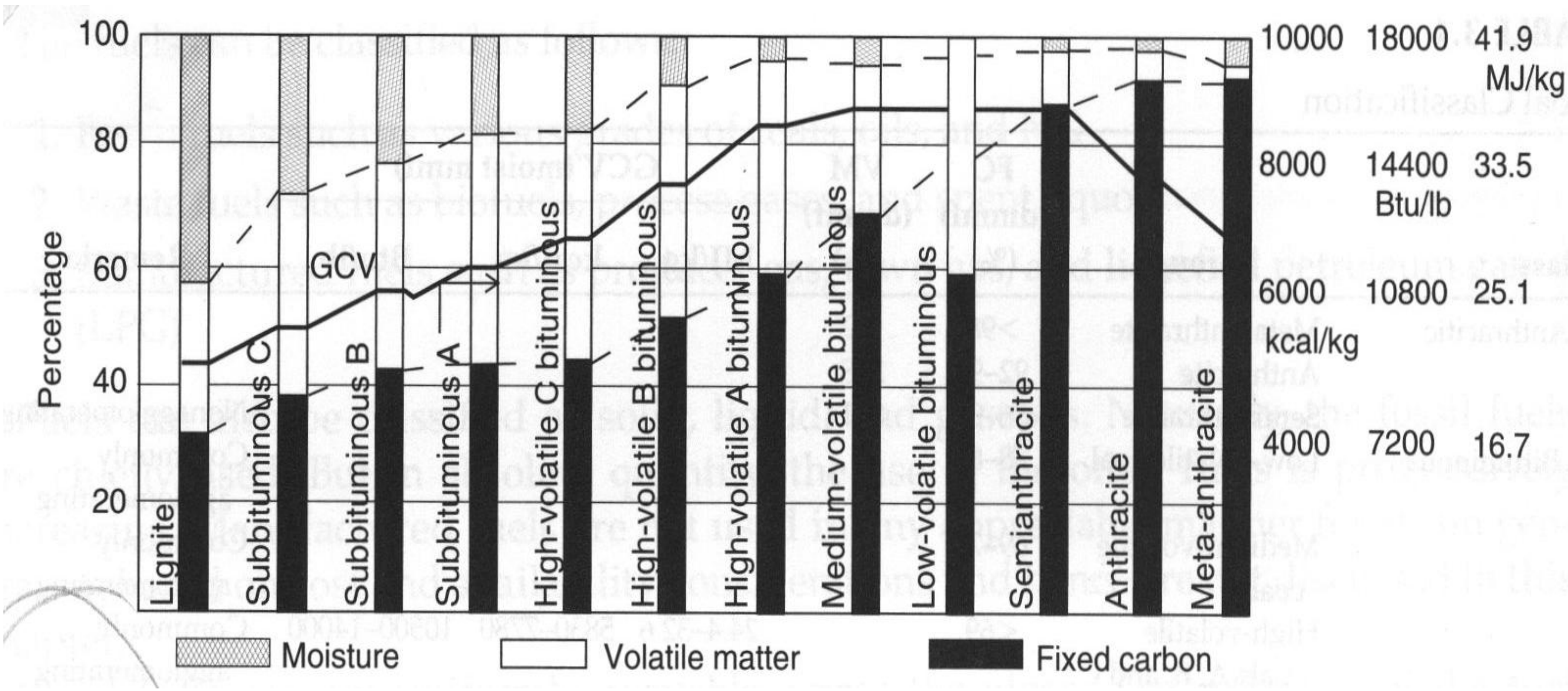
- FC: Fixed Carbon
- VM: Volatile Matter
- dmmf: Dry Mineral Matter Free
- GCV: Gross Calorific Value
- HV: Heating Value
- MM: Mineral Matter
- M: Moisture
- A: Ash

Types of Coal Used in Combustion

- Coal can have a range of compositions and will react accordingly.
- The most ancient coals under high pressure would have converted practically all the vegetable matter into fixed carbon(FC).
- The youngest coals with less pressure contain more volatile matter(VM).
- There are several classifications for coals. In the US, they are classified by rank as per the ASTM D388.
- Rank is measured by the degree of coalification.

Types of Coal Used in Combustion

- The properties used for coal classification consist of the GCV, M, VM, and the agglomerating character.



Types of Coal Used in Combustion

- With increasing rank, FC and GCV increase whereas M and VM decrease.
- The ratio of FC to VM is called the fuel ratio, which increases with rank.
- Obviously, the higher the GCV, the higher the fuel ratio.
- But the GCV drops as there is not enough VM to contribute to the heat value.
- VM and oxygen contents aid in the ignition and enhance combustibility and flame stability.

Coal Types Around the World

Typical As-Received Analysis of Coals from Various Countries

Country	Mine/Area	Ash (%)	M (%)	VM(%)	S (%)	GCV		
						MJ/kg	kcal/kg	Btu/lb
Austria	Grunbach	5–12	4–6	35		25.1	6000	10,790
Australia	Queensland	11.6	1.5	37		28.61	6840	12,300
	NSW West	14.6	2.6	30.0	0.7	27	6450	11,610
	NSW South	11	0.6	23.3	3.74	30.5	7290	13,115
Belgium	Low volatile coal	5–7	4–6	14–18		31.8	7550	13,675
	Dry steam coal	7–9	3–6	8–10		31.4	7505	13,500
Czech Republic	Pilsen	9–16	6–13	30–35		20.9–27.2	4995–6500	8,990–11,700
	Sadovy	8–15	2–7	27–34		27.2–30.1	6500–7200	11,700–12,940
China	Chihli Kaiping	13.3	0.6	26		31.1	7435	13,370
	Chihli Penchihu	11.2	0.7	234		31.4	7505	13,500
France	Loire	17–25	3–5.5	8–18		23–25.1	5500–6000	9,890–10,790
	Nord	5–7	2–4	19–21		29.3–32.2	7000–7700	12,600–13,850
	St. Etienne	12–17	4–5	20–30		26.4–28.1	6310–6715	11,350–12,080
Germany	Aachen (dry steam)	6	4	9–13		31.7	7575	13,630
	Aachen (medium volatile)	6	4	24–30		31.5	7530	13,545
	Bavaria	11	10	35–40		22.5	5380	9,675
	Ruhr	7–9	2–7	10–15		29.7–31.0	7100–7410	12,770–13,330
	Saar	3–7	3–5	38		29.3	7000	12,600
	Saxony	5–6	8	30–36		28.1	6715	12,080
India	Bengal slack	16.2	0.5	9.9		28.3	6760	12,170
	Raniganj	14–17	5–11	34–52		23.8–25.9	5690–4900	10,235–11,140
	Orissa	28–31	7–9	27–31	0.3–1	19.3–20.5	4610–4900	8,300–8,815
	Pench Valley	16–32	2–9	17–33	0.6–2.5	20.1–26	4800–6214	8,640–11,180
	Chanda	13–15	10–11	31–36	0.6–1.7	23–25.5	5500–6095	9,890–10,965
	Tandur	18–22	5–7	26–30	0.5–0.8	21.3–24.3	5090–5810	9,160–10,450

Coal Types Around the World

Indonesia	Palembang dust	6.6	10.0	28.4		26	6215	11,180
Italy		19	5	39		25.5	6095	10,965
Japan	Kyushu Furukawa	14.4	1.6	34.9		29.3	7000	12,600
Poland	Upper Silesia	4–9	3–7	30–35		28.5–29.7	6810–7100	12,255–12,770
	Katowic	6	4	31.6		31.4	7505	13,500
Russia	Kuznets	5–10	1–7	13–25		28.9–31.4	6910–7505	12,430–13,500
	Ural	21	7	25		33.3	7960	14,320
	Donnetz long flame	21.5	7	40	5.7	23.9	5710	10,280
South Africa	Natal	8.6	4.2	16.7	4.18			
	Transvaal	13.3	2.2	27	0.7	28.18	6735	12,120
Spain	Asturias	8–11	5	7–30		29.3–31.4	7000–7505	12,600–13,500
	Zaragoza	11.3	4–6	28.8		26	6215	11,180
Turkey	Isletme	12	7	30		23	5500	9,890
	Zonguldak	15.5	10	27		26	6215	11,180
United Kingdom	Cardiff	3–8	1.0–3.0	25.0–35.0		31.4–33.5	7505–8005	13,500–14,405
	Cumberland	5.5–8.0	2.5–3.5	30.0–36.0		31.0–31.8	7410–7600	13,330–13,680
	Derbyshire	2.0–7.0	4.5–12.0	31.0–39.0		27.2–31.4	6500–7505	11,700–13,500
	Durham	3.0–10.0	2.0–8.0	25.0–35.0		28.1–31.8	6715–7600	12,080–13,680
	Midlands	3.0–7.0	2.0–10.0	21.0–37.0		28.1–31.8	6715–7600	12,080–13,680
United States	Alabama	9.2	3.6	30.5		31.6	7550	13,590
	Maryland	6.0–9.0	1.5–2.5	20.0–40.0		31.8–33.1	7600–7910	13,680–14,230
	Pennsylvania	6.0–9.0	1.0–2.5	20.0–35.0		32.2–33.1	7695–7910	13,850–14,230
	SW Virginia	5.0–7.0	1.5–2.5	20.0–35.0		33.1–34.3	7910–8200	14,230–14,750

How Coal Burns

- A proximate analysis tells us how coal burns, and it assesses four items:

1. Moisture (M)-the total moisture consisting of inherent/interstitial and superficial moisture.
2. Ash (A)-the residue left on burning of the coal.
3. Volatile matter-the gaseous portion that burns above the bed in free space
4. Fixed Carbon-The solid portion of fuel that burns.

Moisture (M)

- The total moisture of as-mined coal varies a great deal. The proportions consist of
  - 5% in low volatile bituminous coal
  - 12% in high-volatile bituminous coal
  - 35-65% in ignites
- On burning, the moisture cools the flue gases, and hence reduces the tendency to form fuel No_x.
- The two types of moisture are inherent moisture and surface moisture.
- Surface moisture leaves the coal at 105°C and inherent moisture leaves the coal at 750°C.

Ash (A)

- Ash is the incombustible mineral matter(MM) left behind when coal is burnt.
- Ash is of two types

1. Adventitious→ shale, clay, pyrites dirt from earth/stone.
2. Inherent→ vegetable matter.

- Ash is composed of compounds Si, Al, Fe, and Ca. To a lesser extent, it consists of Mg, Ti, Na and K.
- Although they are reported as oxides in analysis, they occur in ash as a mix of silicates, oxides, sulphates etc.

Volatile Matter(VM)

- VM is a complex mixture of organic material, which volatilizes quickly on heating at ~300°C and burns in suspension in a furnace.
- The higher the VM, the lower the ignition temperature and greater the combustion speed (easy to ignite and burn coal).
- Coals with less than 15% VM are termed low volatile.
- Expelled VM contains,

1. Water resulting from combustion of H_2.
2. Complex mixtures of H2, O2, CO, CH4, C2H6, and other hydrocarbons(HCs).

Fixed Carbon

- Fixed Carbon is the carbonaceous residue left in the crucible after driving away the VM.
- Fixed carbon needs to be burnt in solid state either on the grate or in the bed in fluidized bed combustion or solid pulverized fuel firing.
- FC=100-(M+A+VM).

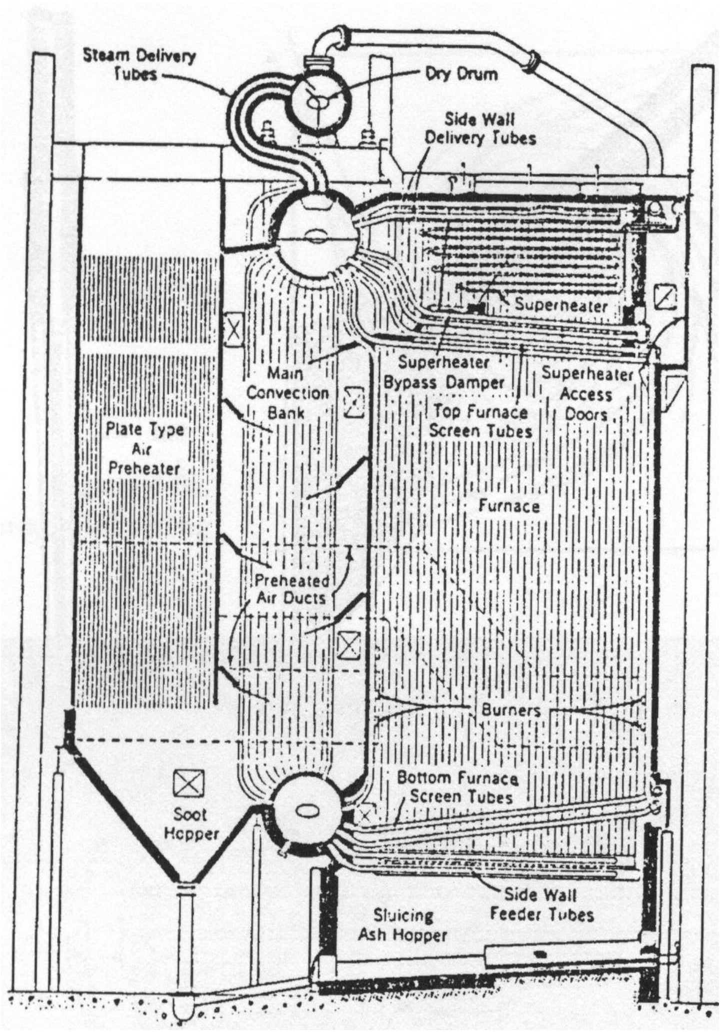
Burners(Jets)-Pulverized Coal

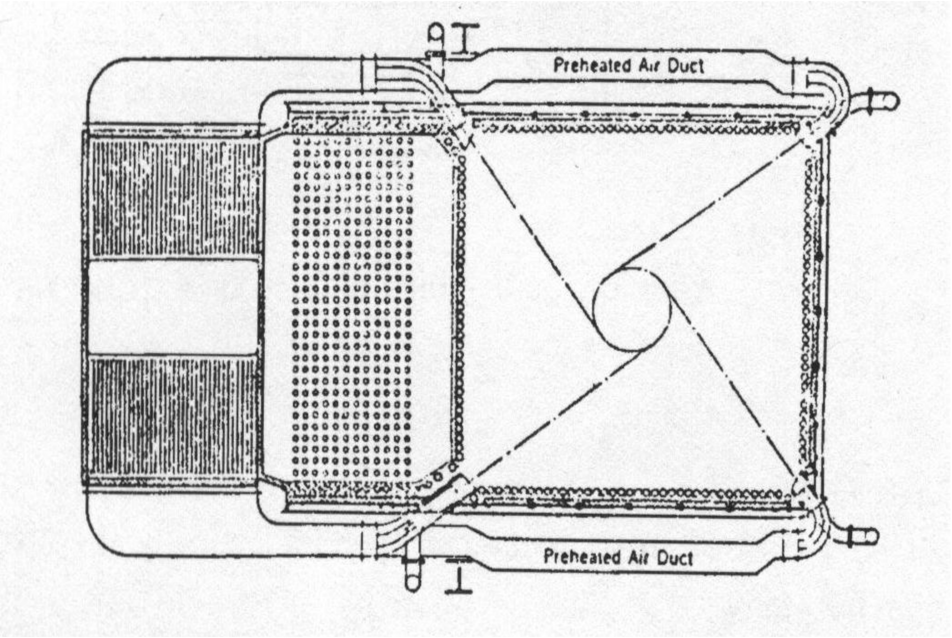
- Purpose is to mix the fuel and air in correct proportions to inject the mixture into the furnace for complete combustion.

1. Air carrying the fuel is primary air.
2. Air injected through separate openings is secondary air.

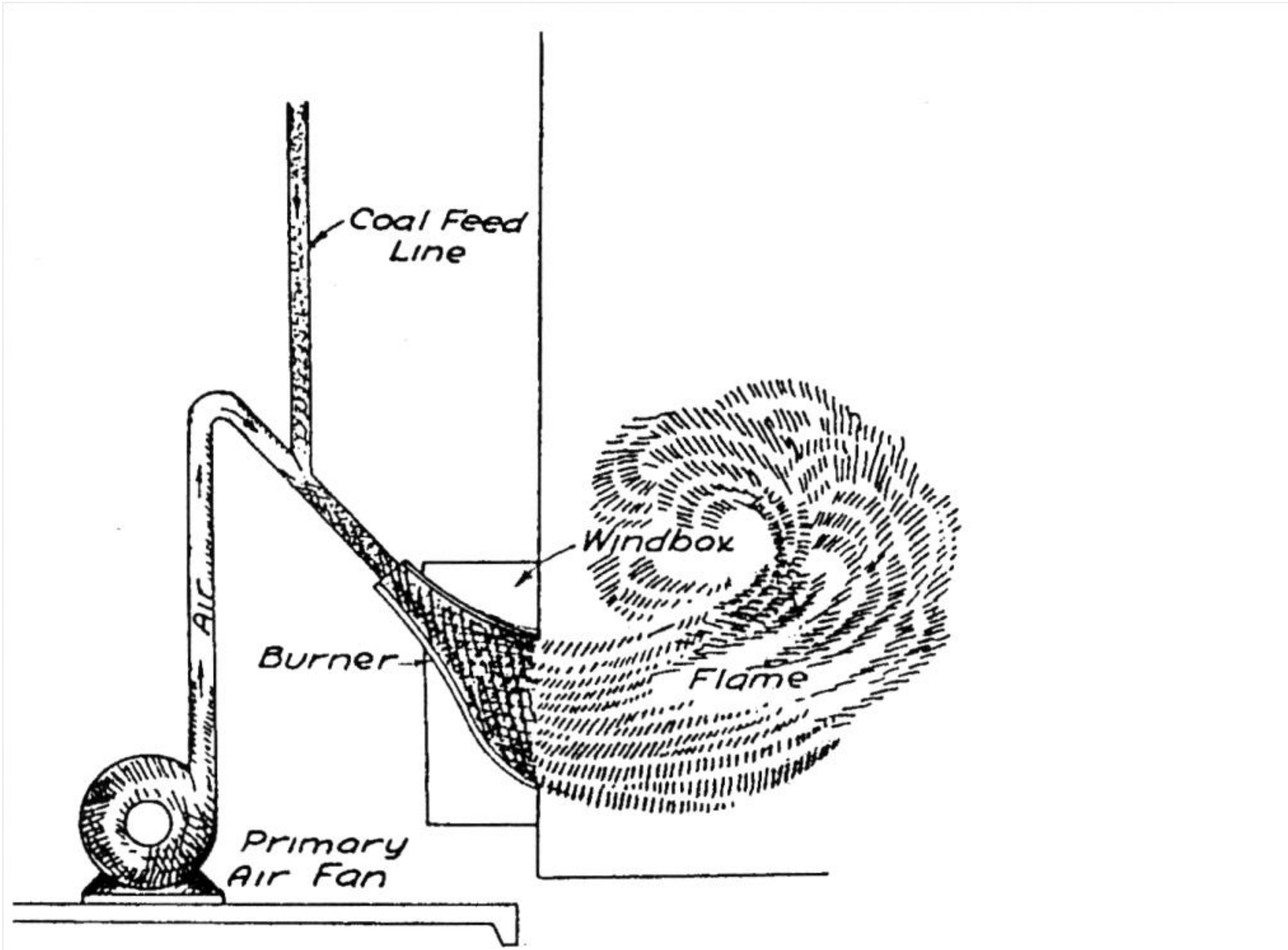
- The most effective turbulence is obtained by placing the burners in the four corners of the furnace, horizontally, in such a manner that the flames impinge one another.
- Cyclonic pattern is observed and high temperatures from the intense turbulence is generated.

Tangential Positioning of Horizontal Flame

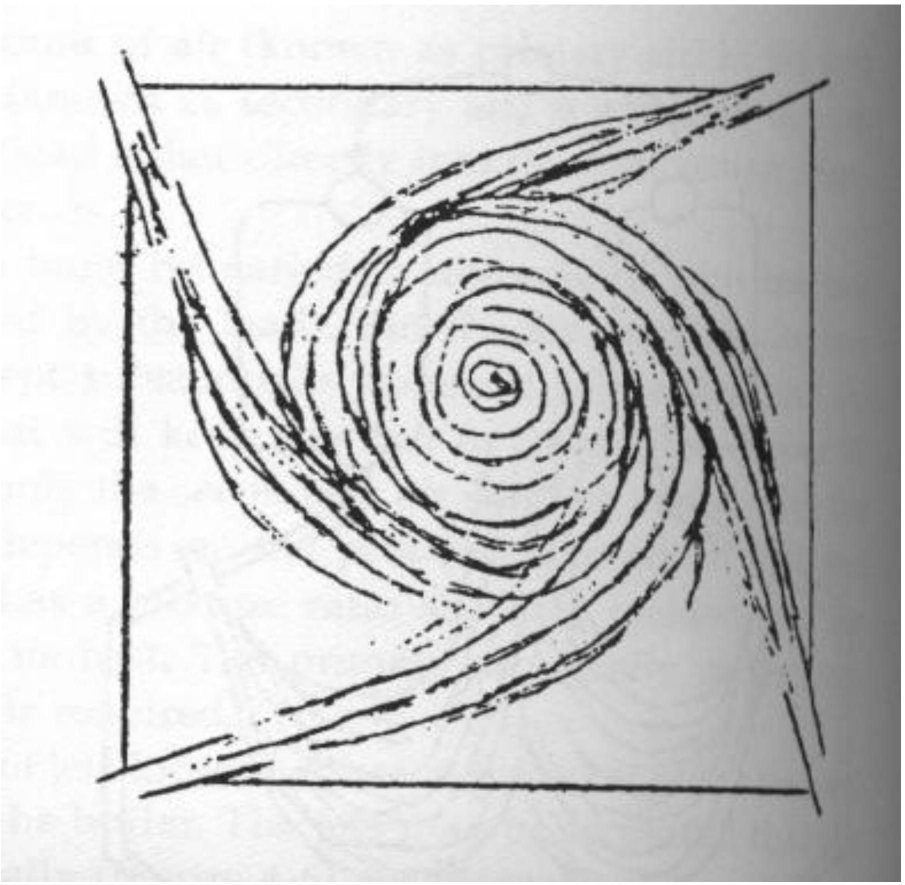




Horizontal Flame Firing



Cyclonic Turbulence



Ash Removal

- The fuels produce soot or fly ash; coal also produces cinders.
- These are small particles of the products of combustion, but they may also include unburned carbon.
- These are carried away in the gasses that ultimately find their way to the atmosphere in flue, stack or chimney.

Actual Coal Composition

Handbook of coal analysis By J. G. Speight

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measured in the laboratory. The moisture in coal ranges from 2 to 15% by weight in bituminous coal to nearly 45% by weight in lignite.

The standard methods of determining the amount of moisture in coal include a variety of test methods designed to differentiate between the various types of

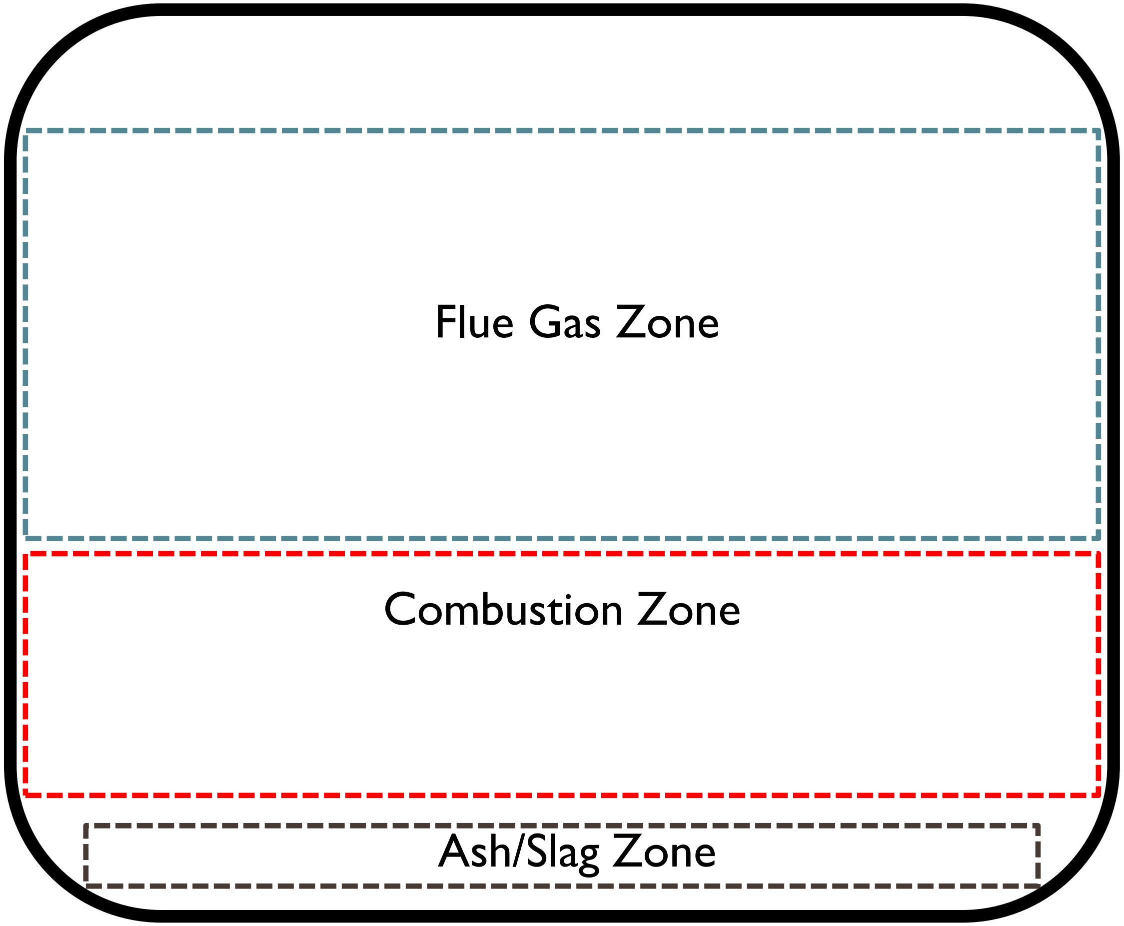
TABLE 3.1 Composition and Property Ranges for Various Ranks of Coal

	Anthracite	Bituminous	Subbituminous	Lignite
Moisture (%)	3–6	2–15	10–25	25–45
Volatile matter (%)	2–12	15–45	28–45	24–32
Fixed carbon (%)	75–85	50–70	30–57	25–30
Ash (%)	4–15	4–15	3–10	3–15
Sulfur (%)	0.5–2.5	0.5–6	0.3–1.5	0.3–2.5
Hydrogen (%)	1.5–3.5	4.5–6	5.5–6.5	6–7.5
Carbon (%)	75–85	65–80	55–70	35–45
Nitrogen (%)	0.5–1	0.5–2.5	0.8–1.5	0.6–1.0
Oxygen (%)	5.5–9	4.5–10	15–30	38–48
Btu/lb	12,000–13,500	12,000–14,500	7500–10,000	6000–7500
Density (g/mL)	1.35–1.70	1.28–1.35	1.35–1.40	1.40–1.45

Actual Coal Composition

- Stable combustion conditions requires the right amounts of fuels and oxygen. The combustion products are heat energy, carbon dioxide, water vapour, nitrogen, and other gases (excluding oxygen).
- In theory there is a specific amount of oxygen needed to completely burn a given amount of fuel. In practice, burning conditions are never ideal.
- Therefore, more air than ideal must be supplied to burn all fuel completely. The amount of air more than the theoretical requirement is referred to as **excess air**.
- Pulverized coal-fired boilers may run with *20* percent excess air.
- Typical values of excess air for some common fuels are shown in the table below:

Thermodynamic Partition Analysis



Carbon Oxygen Ratio

Fuel	Excess of Air (%)
Anthracite	40
Coke oven gas	5 - 10
Natural Gas	5 - 10
Coal, pulverized	15 - 20
Coal, stoker	20 - 30
Oil (No. 2 and No. 6)	10 to 20
Semi anthracite, hand firing	70 to 100
Semi anthracite, with stoker	40 to 70
Semi anthracite, with traveling grate	30 to 60

The Setup

Input 1		
Anthracite		
H_20	4.50	-
C	80.00	-
Ash	9.50	-
Vm	6.00	-
Total	100.00	-

Input 3		
Lignite		
H_20	35.00	-
C	28.00	-
Ash	9.00	-
Vm	28.00	-
Total	100.00	-

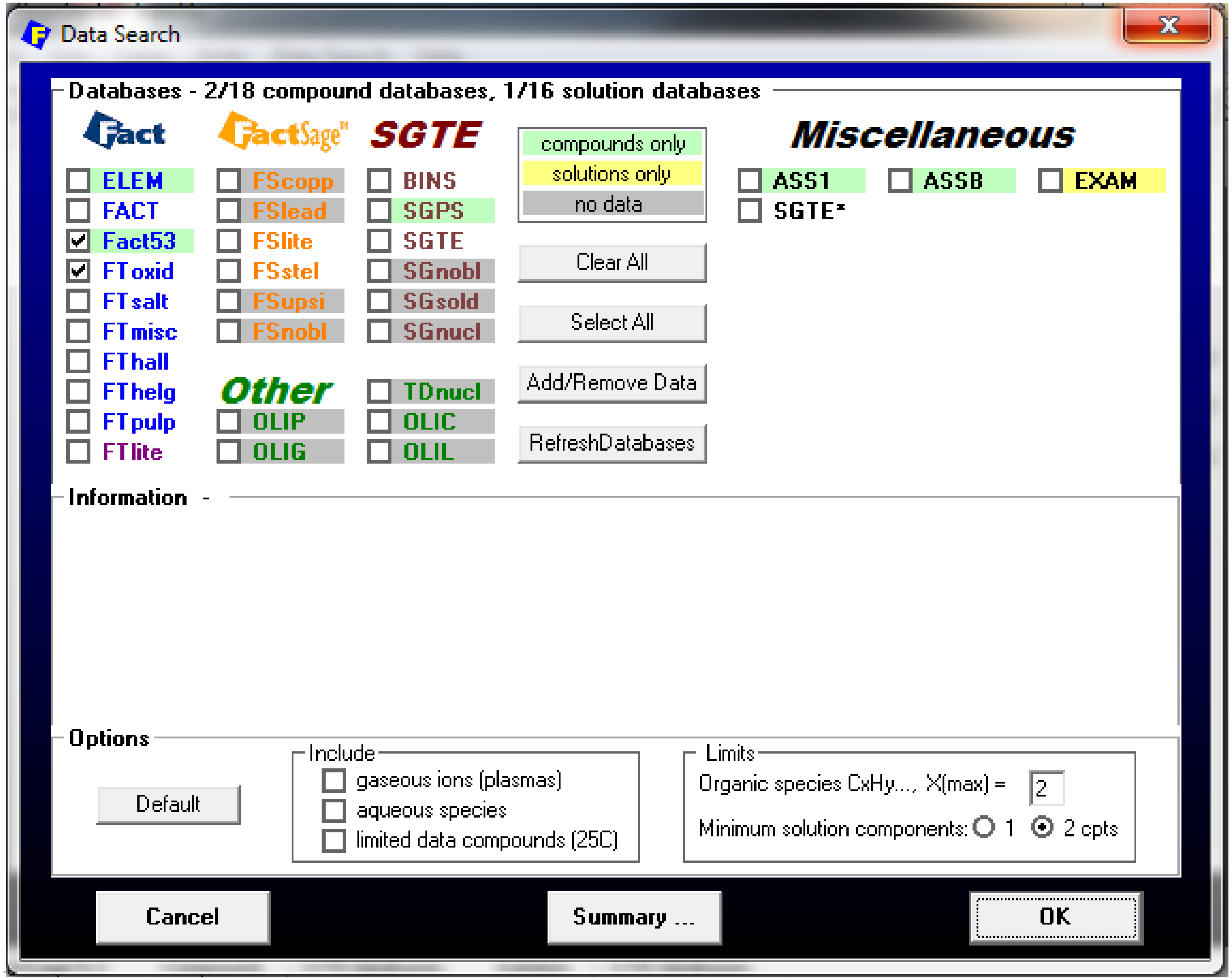
Input 2		
Subbituminous		
H_20	17.50	-
C	35.00	-
Ash	11.00	-
Vm	36.50	-
Total	100.00	-

The Setup

Ash Input			
Oxide	**Moles**	**Grams**	**Percentage**
SiO2	6.657346	400	41.2360%
Al2O3	0.980767	100	10.3090%
FeS2	0.249803	29.970648	3.0897%
CaO	2.674893	150	15.4635%
MgO	1.984915	80	8.2472%
Na2O	1.129415	70	7.2163%
K2O	0.318488	30	3.0927%
TiO2	0.375634	30	3.0927%
SO3	0	0	0.0000%
Fe2O3	0.501323	80.054832	8.2529%
Total	14.87259	970.02548	100.00%

Volatile Material Input			
Oxide	**Moles**	**Grams**	**Percentage**
CO	100.00	4.55	8.764722%
CO_2	100.00	2.63	5.074349%
CH_4	200.00	20.00	38.563026%
C_2H_6	200.00	11.11	21.423903%
C_3H_8	200.00	7.69	14.831933%
C_4H_{10}	200.00	5.88	11.342066%
Total	1000.00	51.86	100.00%

The Setup


Data Search
Databases - 2/18 compound databases, 1/16 solution databases
Fact
FactSage
SGTE
compounds only
solutions only
no data
Miscellaneous
ELEM
FACT
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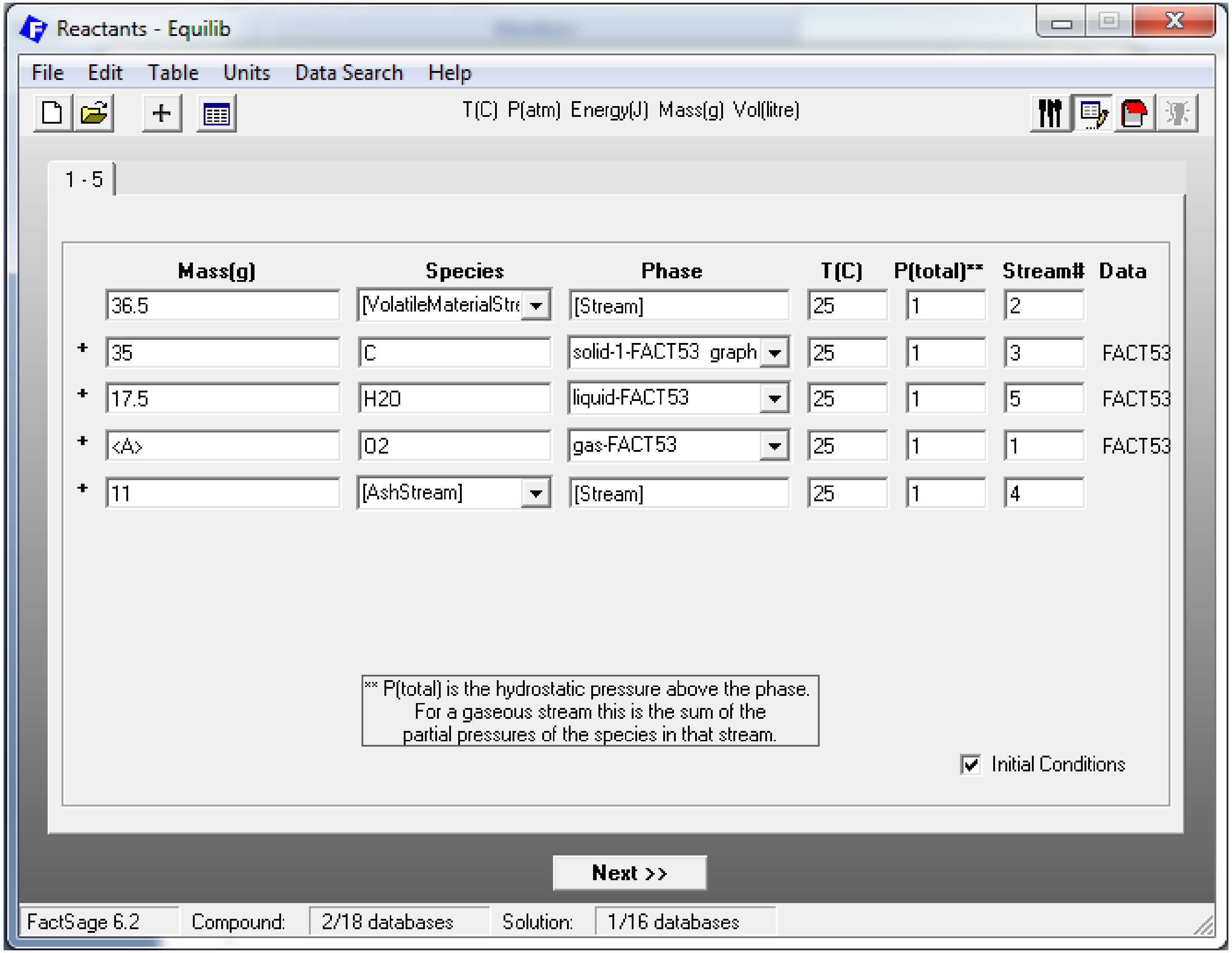
FToxid
FTsalt
FTmisc
FThall
FThelg
FTpulp
FTlite
FScopp
FSlead
FSlite
FSstel
FSupsi
FSnobl
BINS
SGPS
SGTE
SGnobl
SGsold
SGnucl
Other
TDnucl
OLIP
OLIC
OLIG
OLIL
Clear All
Select All
Add/Remove Data
RefreshDatabases
ASS1
ASSB
EXAM
SGTE*
Information -
Options
Default
Include
gaseous ions (plasmas)
aqueous species
limited data compounds (25C)
Limits
Organic species CxHy..., X(max) = 2
Minimum solution components: 1 2 cpts
Cancel
Summary ...
OK

The Setup



Reactants - Equilib
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T(C) P(atm) Energy(J) Mass(g) Vol(litre)
1 - 5
Mass(g) Species Phase T(C) P(total)** Stream# Data
36.5 [VolatileMaterialStre [Stream] 25 1 2
+ 35 C solid-1-FACT53 graph 25 1 3 FACT53
+ 17.5 H2O liquid-FACT53 25 1 5 FACT53
+ <A> O2 gas-FACT53 25 1 1 FACT53
+ 11 [AshStream] [Stream] 25 1 4
** P(total) is the hydrostatic pressure above the phase. For a gaseous stream this is the sum of the partial pressures of the species in that stream.
Initial Conditions
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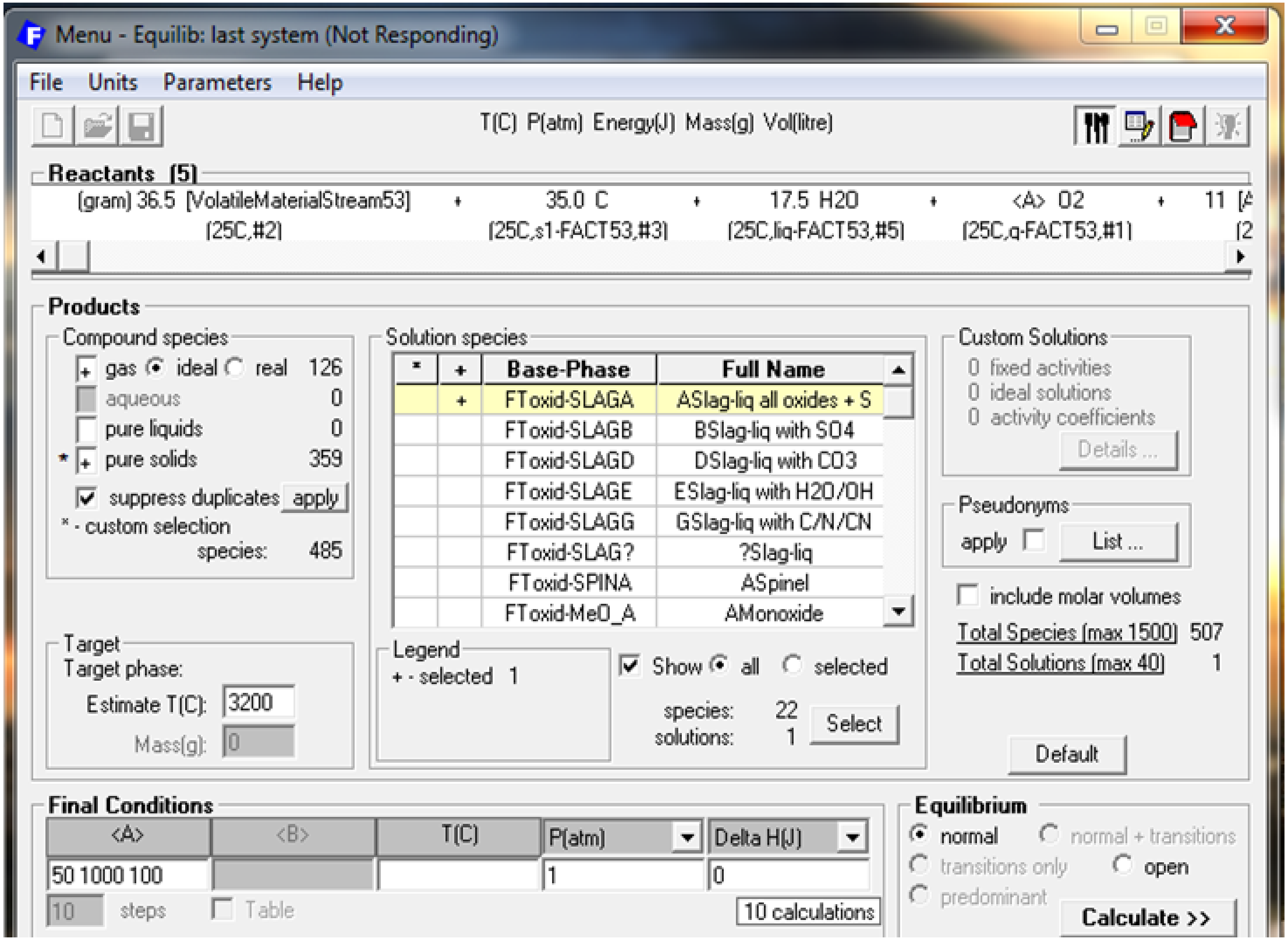
Compound: 2/18 databases
Solution: 1/16 databases

The Setup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T(C) P(atm) Energy(J) Mass(g) Vol(litre)
Reactants (5)
(gram) 36.5 [VolatileMaterialStream53]
[25C,#2]
+
35.0 C
[25C,s1-FACT53,#3]
+
17.5 H2O
[25C,liq-FACT53,#5]
+
<A> O2
[25C,g-FACT53,#1]
+
11
Products
Compound species
gas
ideal
real
126
aqueous
0
pure liquids
0
pure solids
359
suppress duplicates
apply
* - custom selection
species:
485
Solution species
Base-Phase
Full Name
FToxid-SLAGA
ASlag-liq all oxides + S
FToxid-SLAGB
BSlag-liq with SO4
FToxid-SLAGD
DSlag-liq with CO3
FToxid-SLAGE
ESlag-liq with H2O/OH
FToxid-SLAGG
GSlag-liq with C/N/CN
FToxid-SLAG?
?Slag-liq
FToxid-SPINA
ASpinel
FToxid-MeO_A
AMonoxide
Custom Solutions
0 fixed activities
0 ideal solutions
0 activity coefficients
Details ...
Pseudonyms
apply
List ...
include molar volumes
Total Species (max 1500) 507
Total Solutions (max 40) 1
Target
Target phase:
Estimate T(C):
3200
Mass(g):
0
Legend
+ - selected 1
Show
all
selected
species: 22
solutions: 1
Select
Default
Final Conditions
<A>
<B>
T(C)
P(atm)
Delta H(J)
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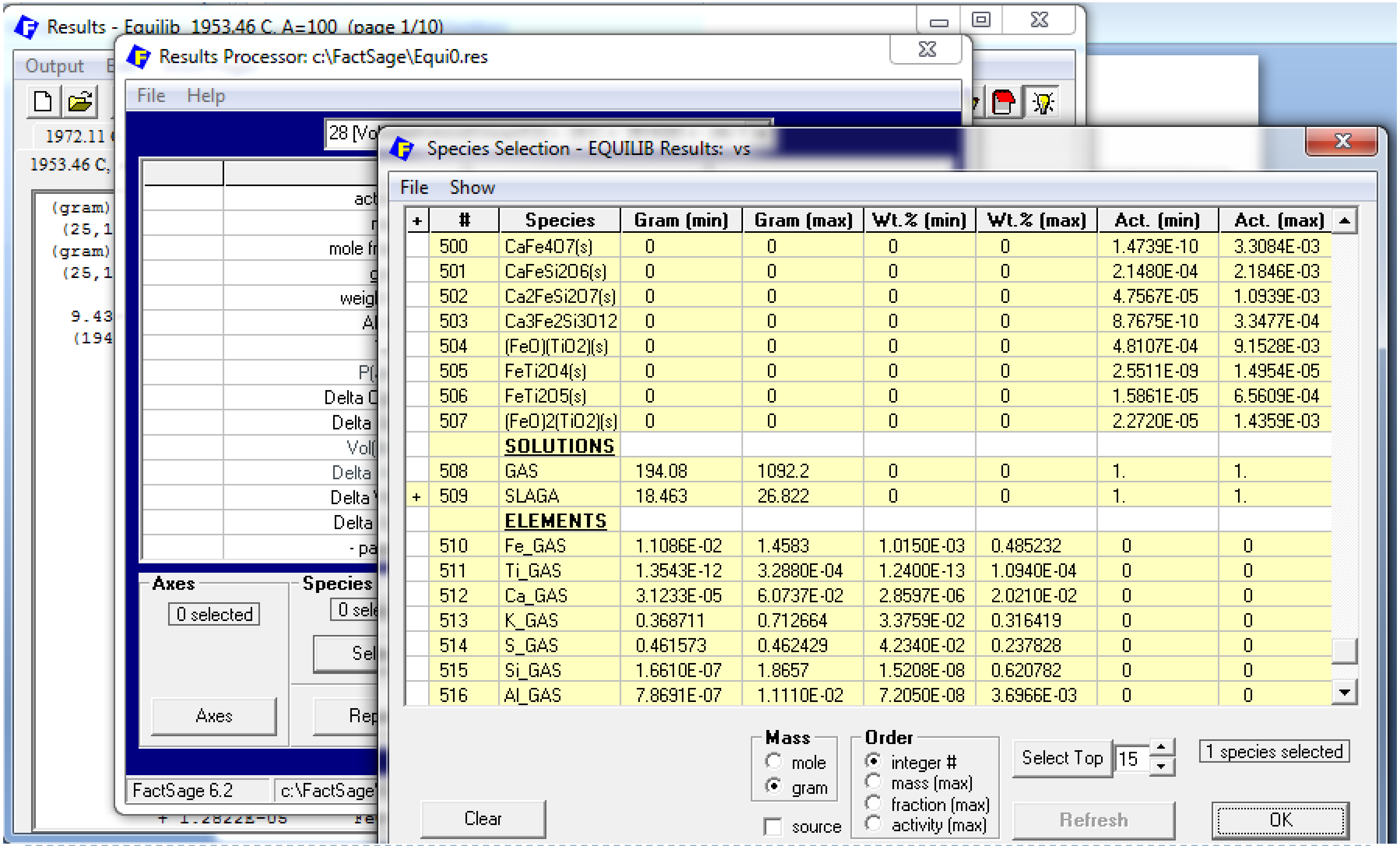
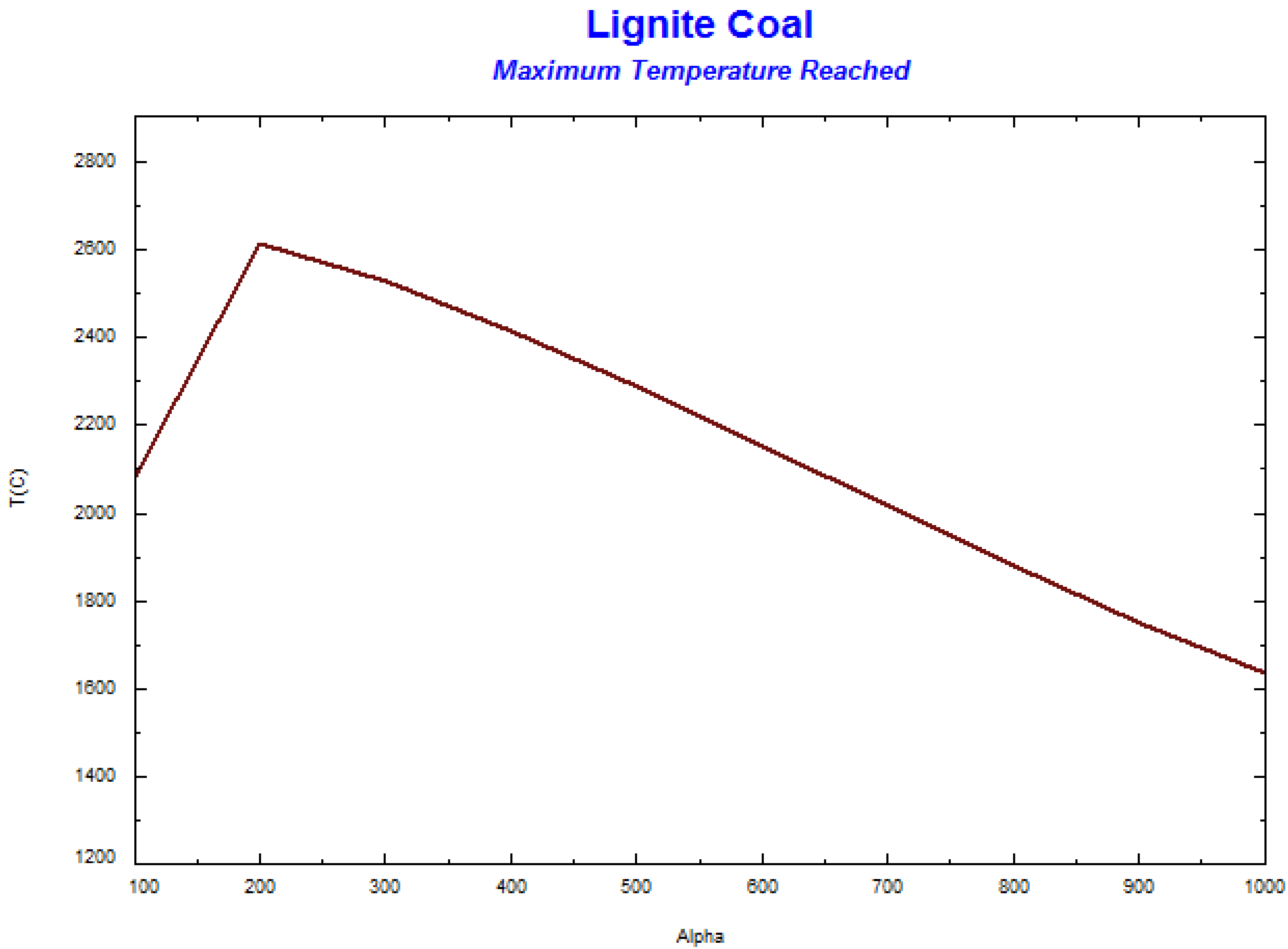
Calculate >>

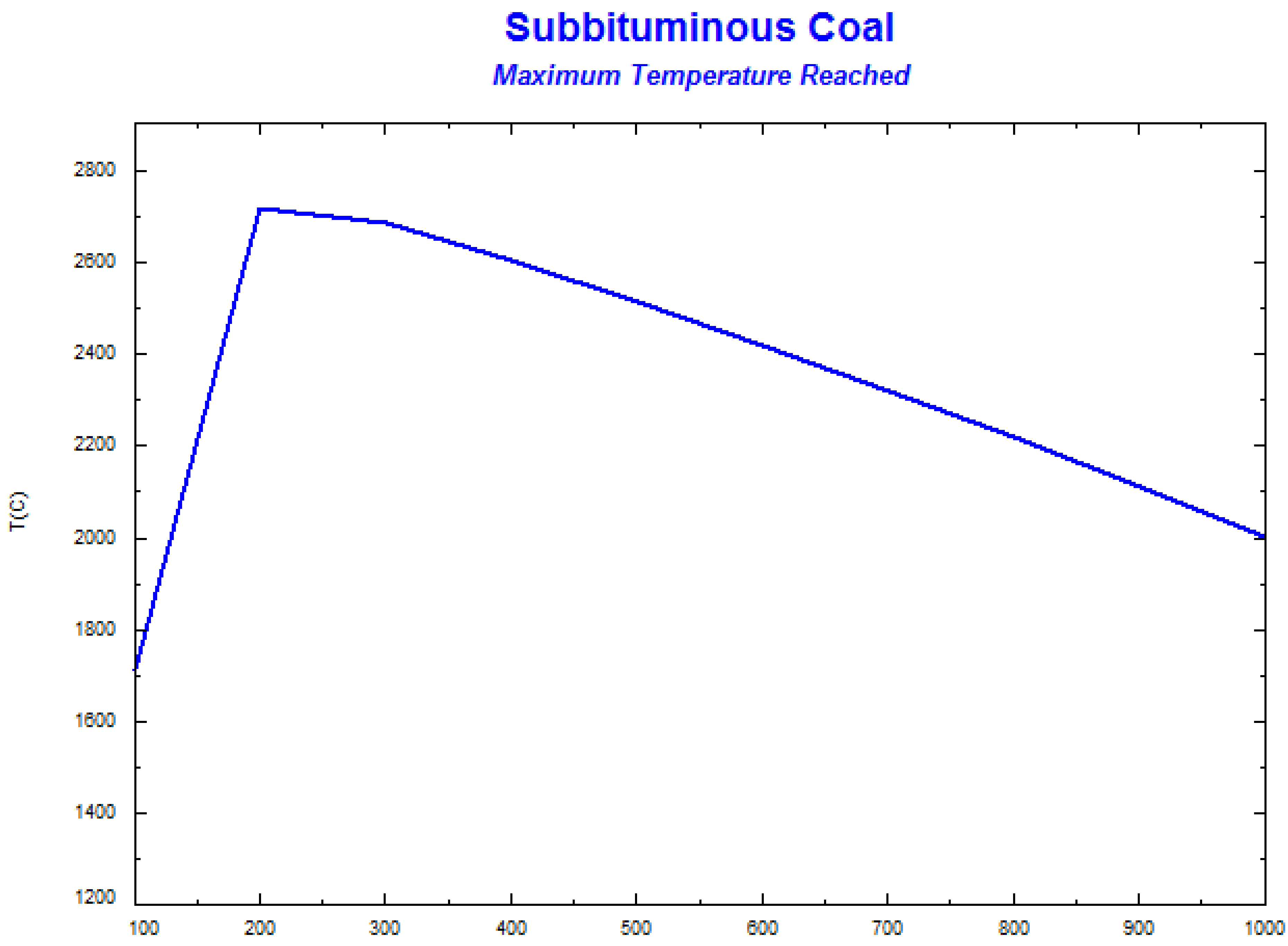
The Setup

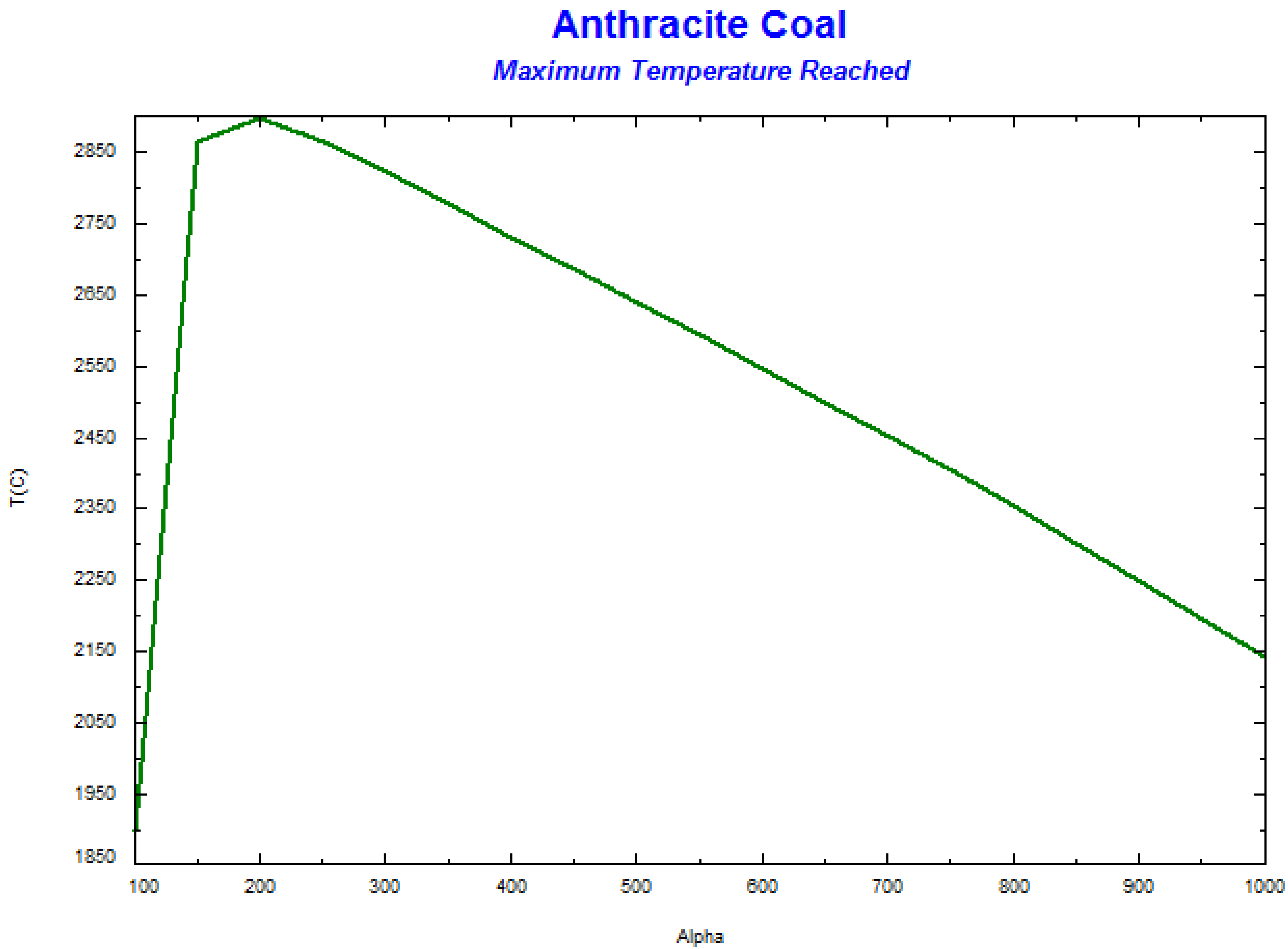


+	#	Species	Gram (min)	Gram (max)	Wt.% (min)	Wt.% (max)	Act. (min)	Act. (max)
	500	CaFe4O7(s)	0	0	0	0	1.4739E-10	3.3084E-03
	501	CaFeSi2O6(s)	0	0	0	0	2.1480E-04	2.1846E-03
	502	Ca2FeSi2O7(s)	0	0	0	0	4.7567E-05	1.0939E-03
	503	Ca3Fe2Si3O12	0	0	0	0	8.7675E-10	3.3477E-04
	504	(FeO)(TiO2)(s)	0	0	0	0	4.8107E-04	9.1528E-03
	505	FeTi2O4(s)	0	0	0	0	2.5511E-09	1.4954E-05
	506	FeTi2O5(s)	0	0	0	0	1.5861E-05	6.5609E-04
	507	(FeO)2(TiO2)(s)	0	0	0	0	2.2720E-05	1.4359E-03
		SOLUTIONS						
	508	GAS	194.08	1092.2	0	0	1.	1.
+	509	SLAGA	18.463	26.822	0	0	1.	1.
		ELEMENTS						
	510	Fe_GAS	1.1086E-02	1.4583	1.0150E-03	0.485232	0	0
	511	Ti_GAS	1.3543E-12	3.2880E-04	1.2400E-13	1.0940E-04	0	0
	512	Ca_GAS	3.1233E-05	6.0737E-02	2.8597E-06	2.0210E-02	0	0
	513	K_GAS	0.368711	0.712664	3.3759E-02	0.316419	0	0
	514	S_GAS	0.461573	0.462429	4.2340E-02	0.237828	0	0
	515	Si_GAS	1.6610E-07	1.8657	1.5208E-08	0.620782	0	0
	516	Al_GAS	7.8691E-07	1.1110E-02	7.2050E-08	3.6966E-03	0	0



Lignite Coal
Maximum Temperature Reached
T(C)
Alpha
1200
1400
1600
1800
2000
2200
2400
2600
2800
100
200
300
400
500
600
700
800
900
1000

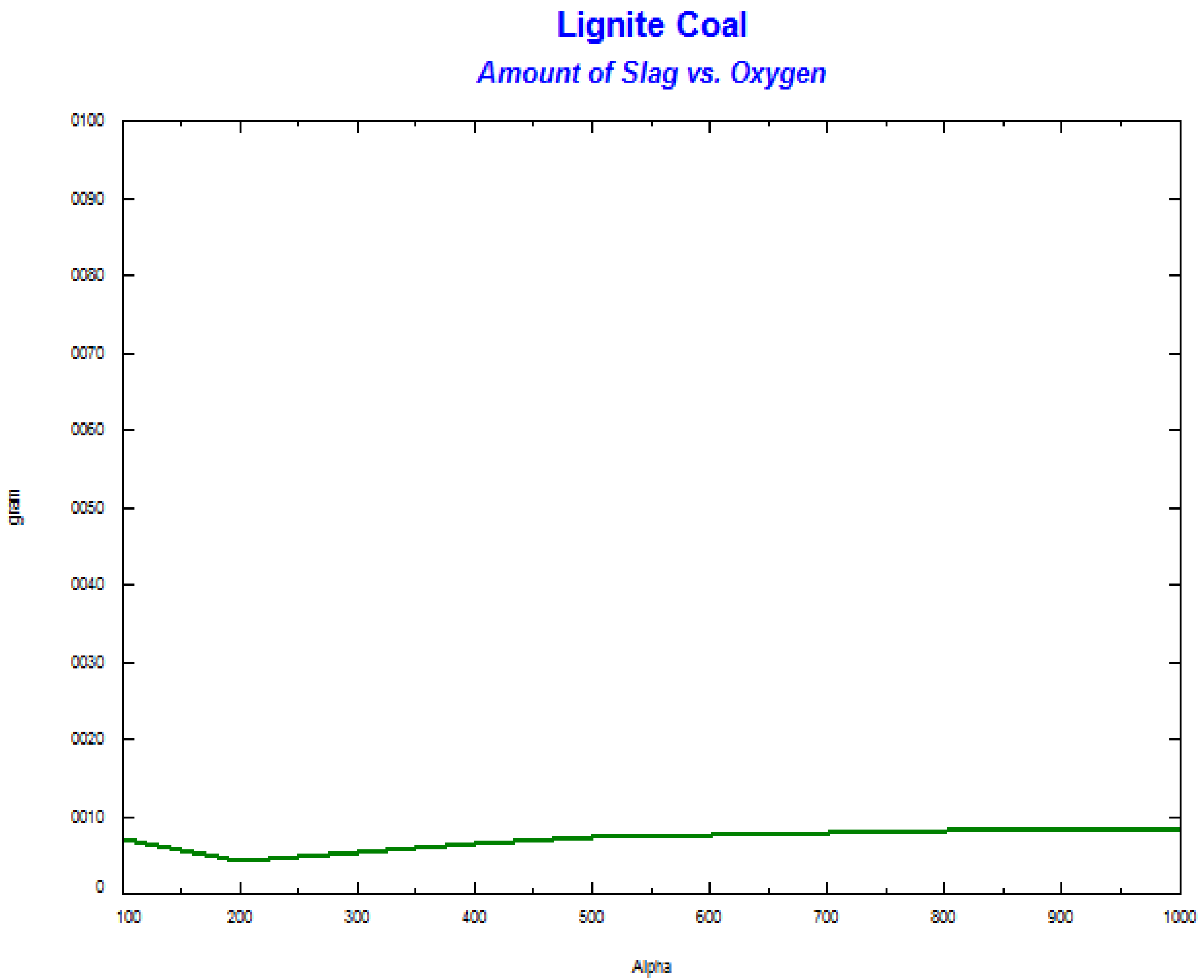

Subbituminous Coal
Maximum Temperature Reached
T(C)
2800
2600
2400
2200
2000
1800
1600
1400
1200
100
200
300
400
500
600
700
800
900
1000



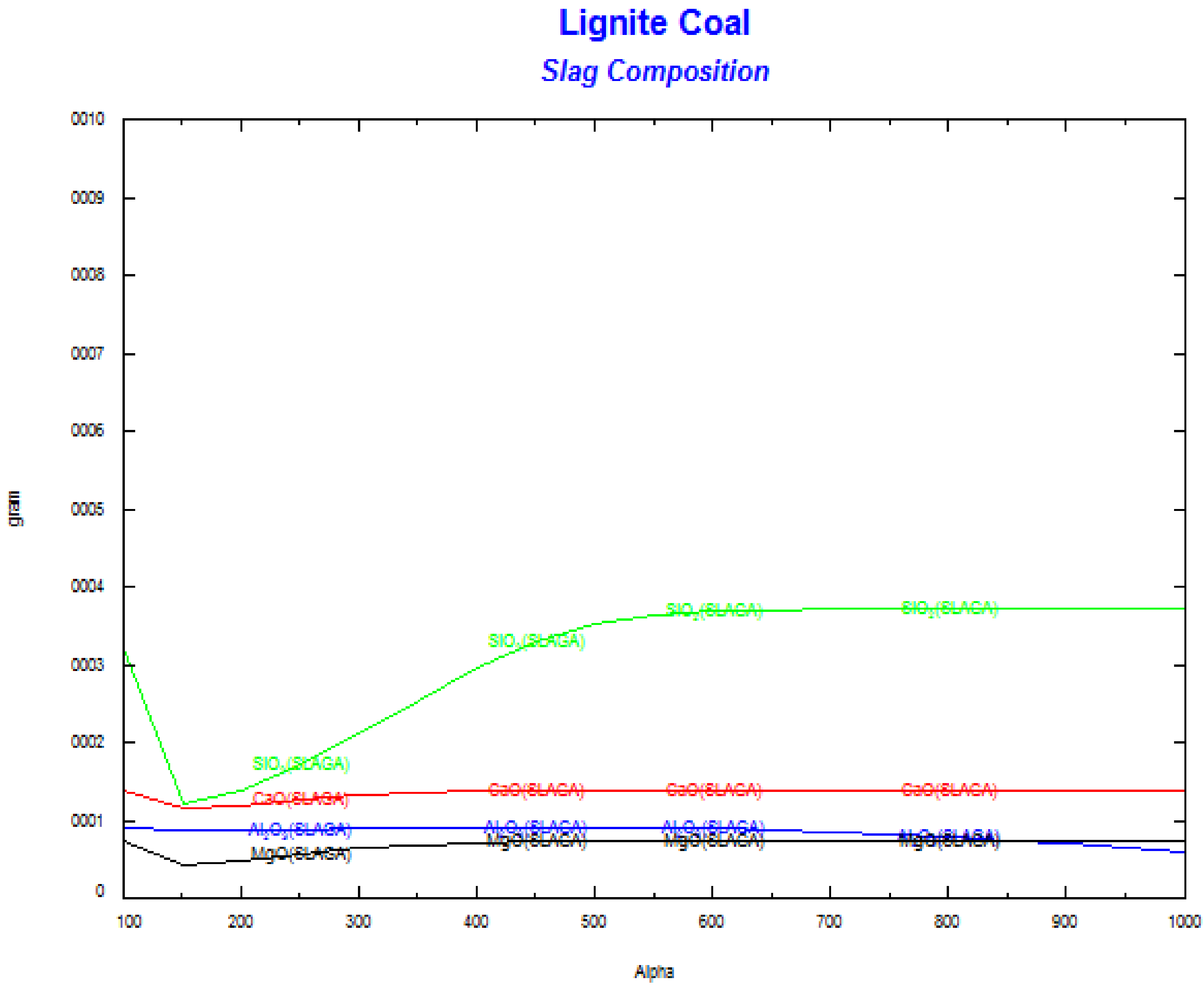
Anthracite Coal
Maximum Temperature Reached
T(C)
2850
2750
2650
2550
2450
2350
2250
2150
2050
1950
1850
100
200
300
400
500
600
700
800
900
1000
Alpha

Results-Temperature vs. Oxygen Flux

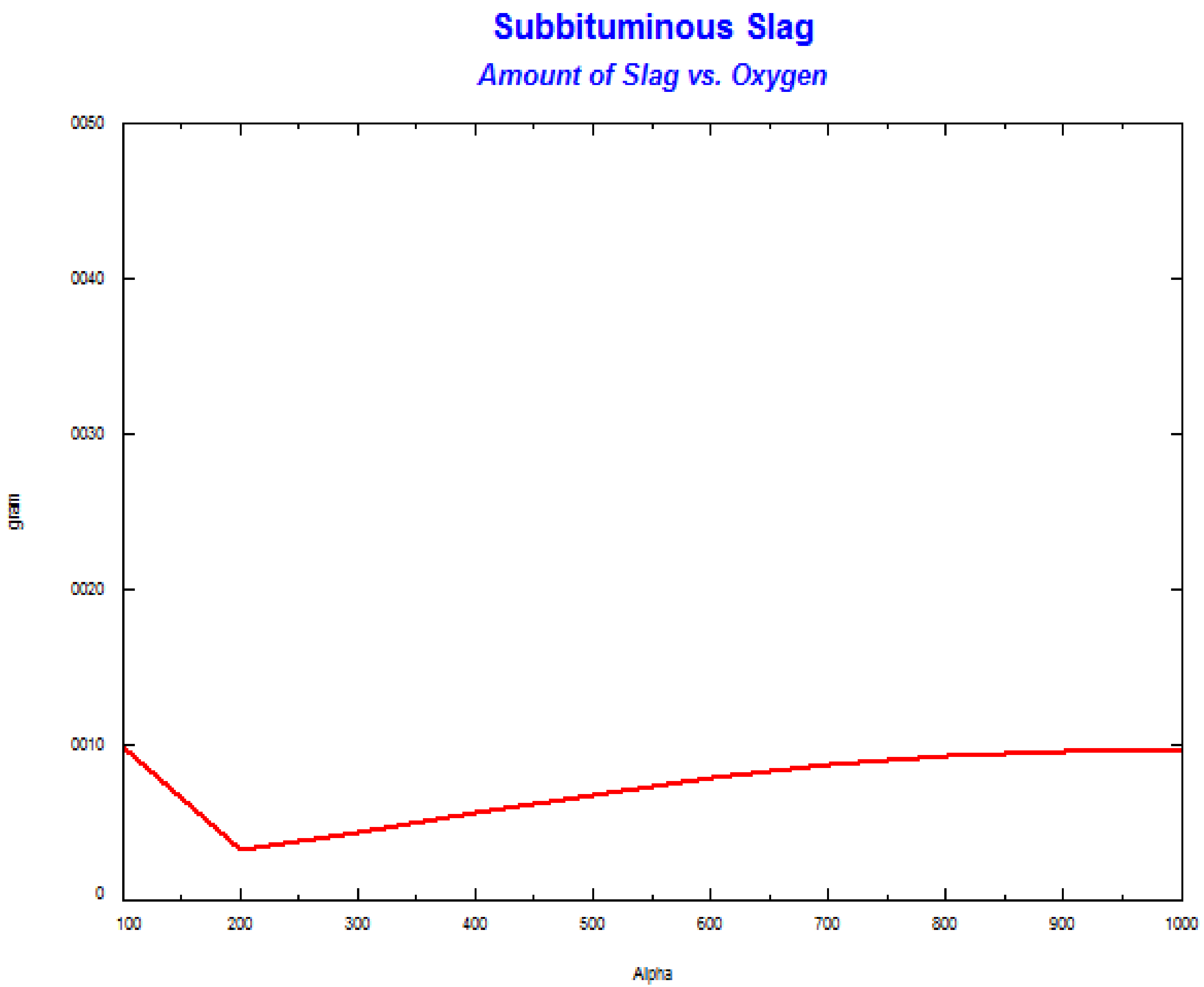
- As expected, the coal with the highest caloric value will yield higher maximum temperature.
- The lignite coal will react with an optimal amount of oxygen(200g) to reach a maximum temperature of 2600°C.
- The subbituminous coal will react with an optimal amount of oxygen(200g) to reach a maximum temperature of 2700°C.
- The anthracite coal will react with an optimal amount of oxygen(200g) to reach a maximum temperature of 2900°C.



Lignite Coal
Amount of Slag vs. Oxygen
0100
0090
0080
0070
0060
0050
0040
0030
0020
0010
0
gram
100
200
300
400
500
600
700
800
900
1000
Alpha



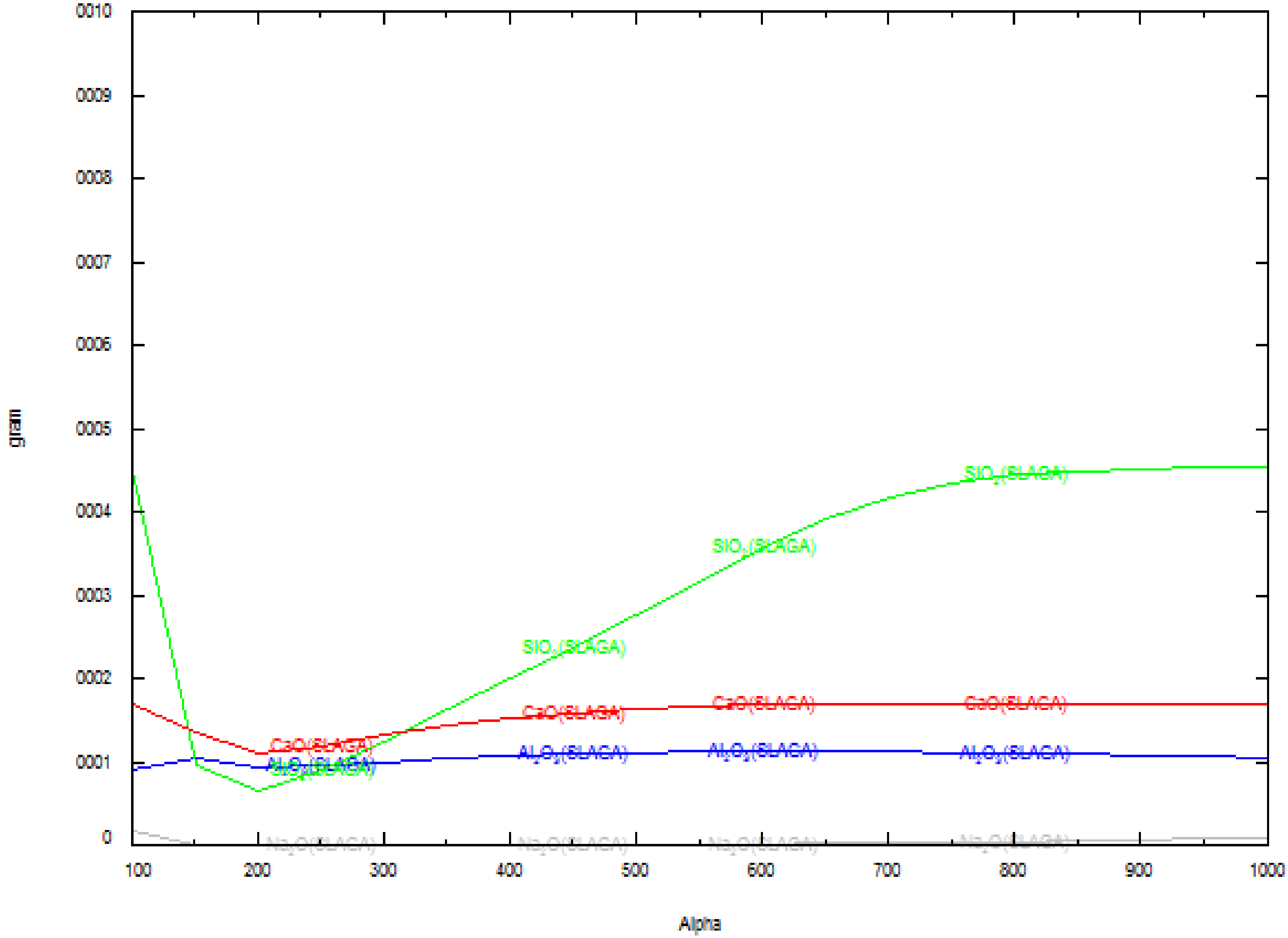
Lignite Coal
Slag Composition
gram
0010
0009
0008
0007
0006
0005
0004
0003
0002
0001
0
100
200
300
400
500
600
700
800
900
1000
Alpha
SIO_2(SLAGA)
CaO(SLAGA)
Al_2O_3(SLAGA)
MgO(SLAGA)

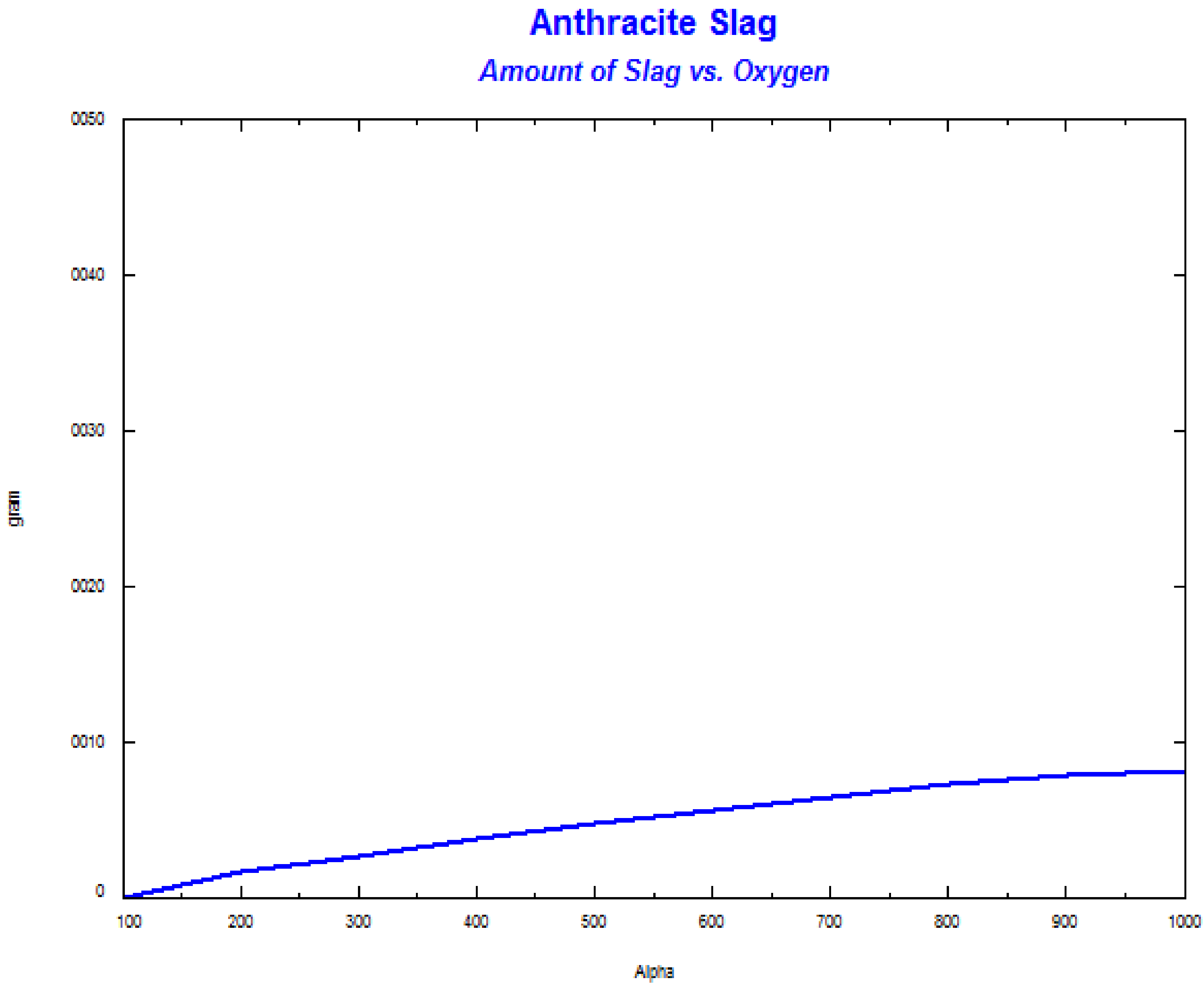


Subbituminous Slag
Amount of Slag vs. Oxygen
0050
0040
0030
0020
0010
0
gram
100
200
300
400
500
600
700
800
900
1000
Alpha

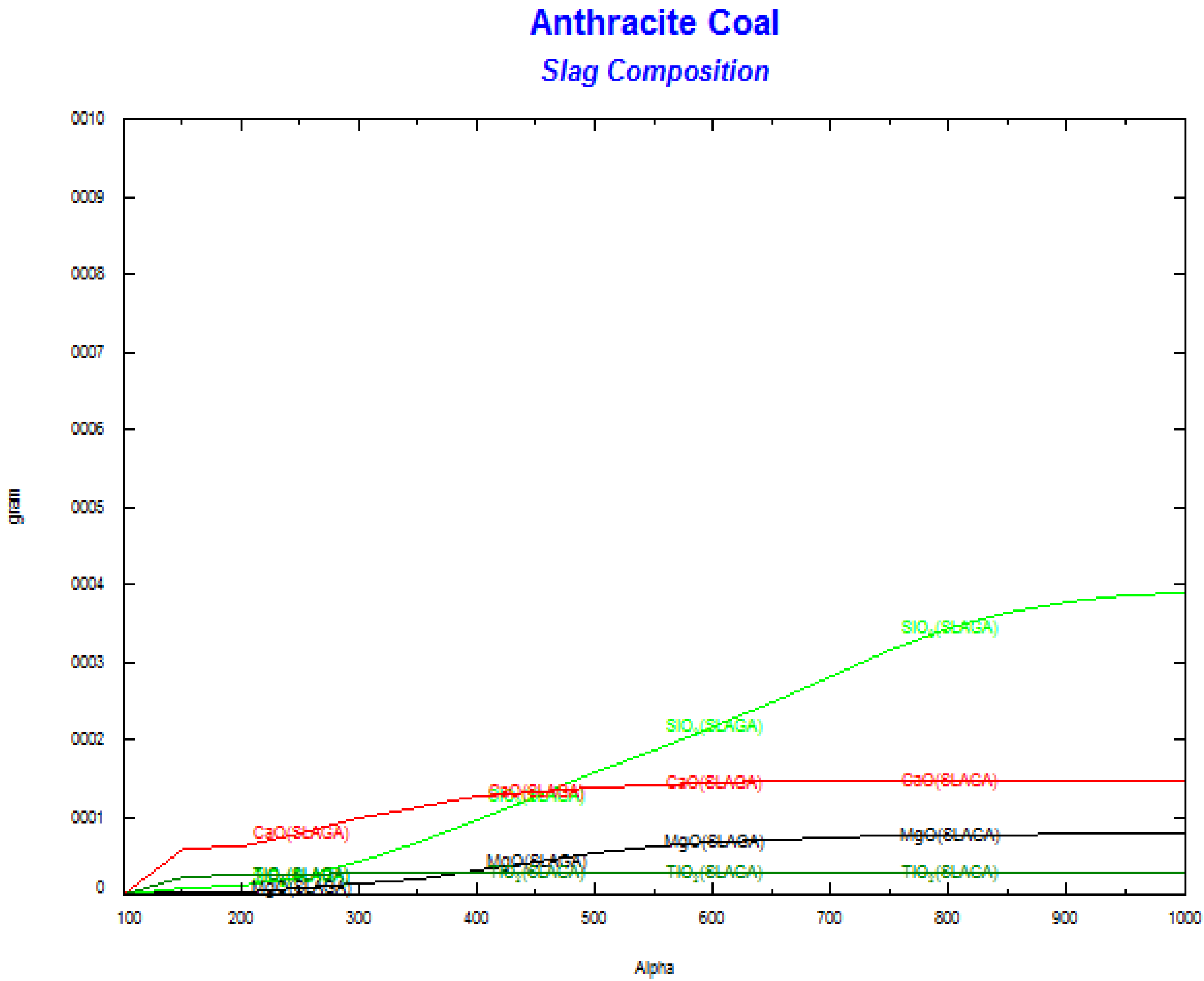
Subbituminous Coal

Slag Composition





Anthracite Slag
Amount of Slag vs. Oxygen
0050
0040
0030
0020
0010
0
gram
100
200
300
400
500
600
700
800
900
1000
Alpha



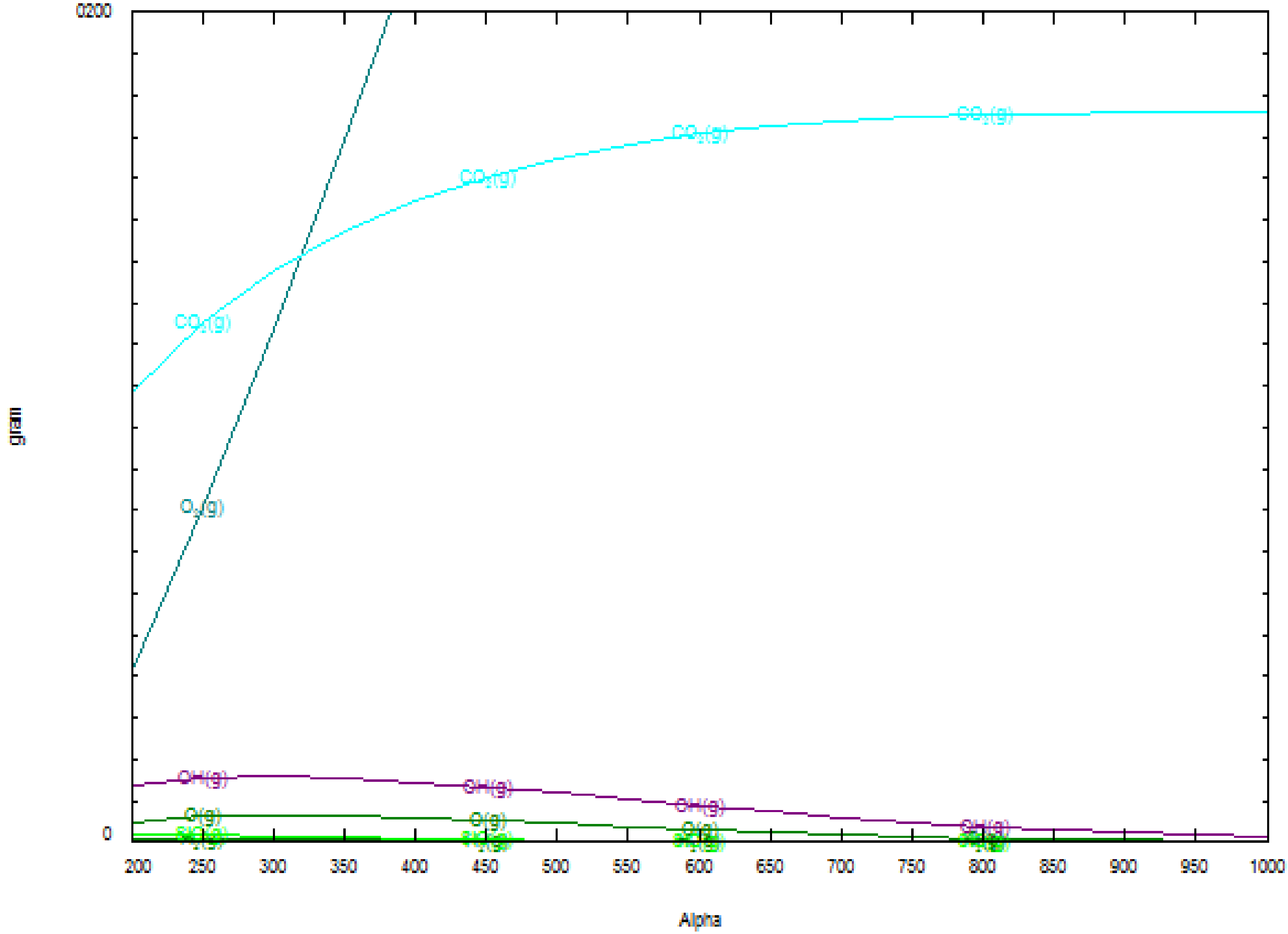
Anthracite Coal
Slag Composition
gram
Alpha
0010
0009
0008
0007
0006
0005
0004
0003
0002
0001
0
100
200
300
400
500
600
700
800
900
1000
SIO2(SLAGA)
CaO(SLAGA)
MgO(SLAGA)
TIO2(SLAGA)

Results-Slag vs. Oxygen Flux

- The total slag composition for lignite and subbituminous follow a similar shape, but is different for anthracite coal.
- The lignite and subbituminous coal slag will be minimum at the quantity of oxygen which the maximum temperature is reached .
- However, the anthracite coal has an initial slag composition of zero which indicates a much cleaner burn than the other two coals.
- The anthracite coal is more efficient.

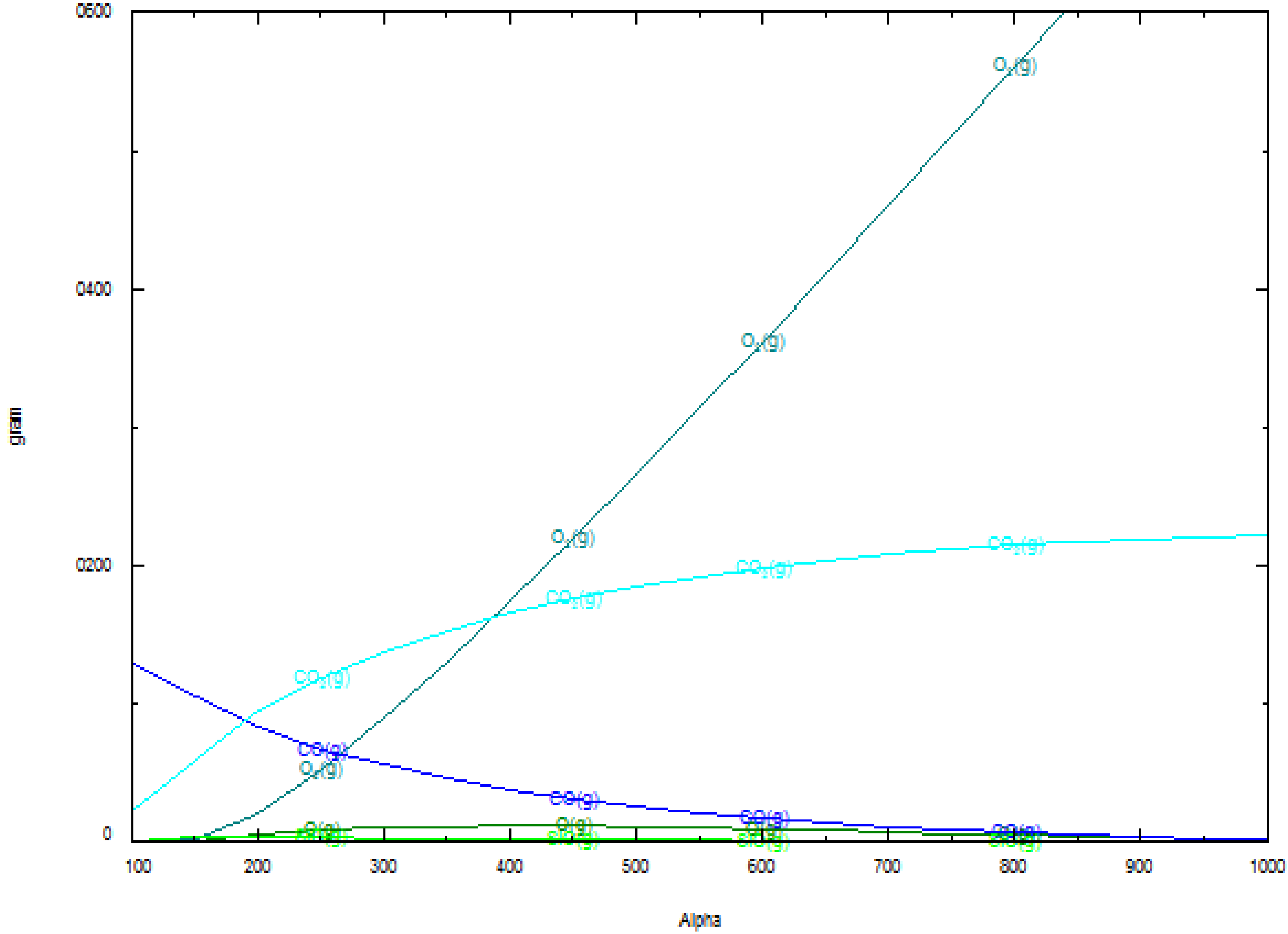
Lignite Coal

Gas Composition



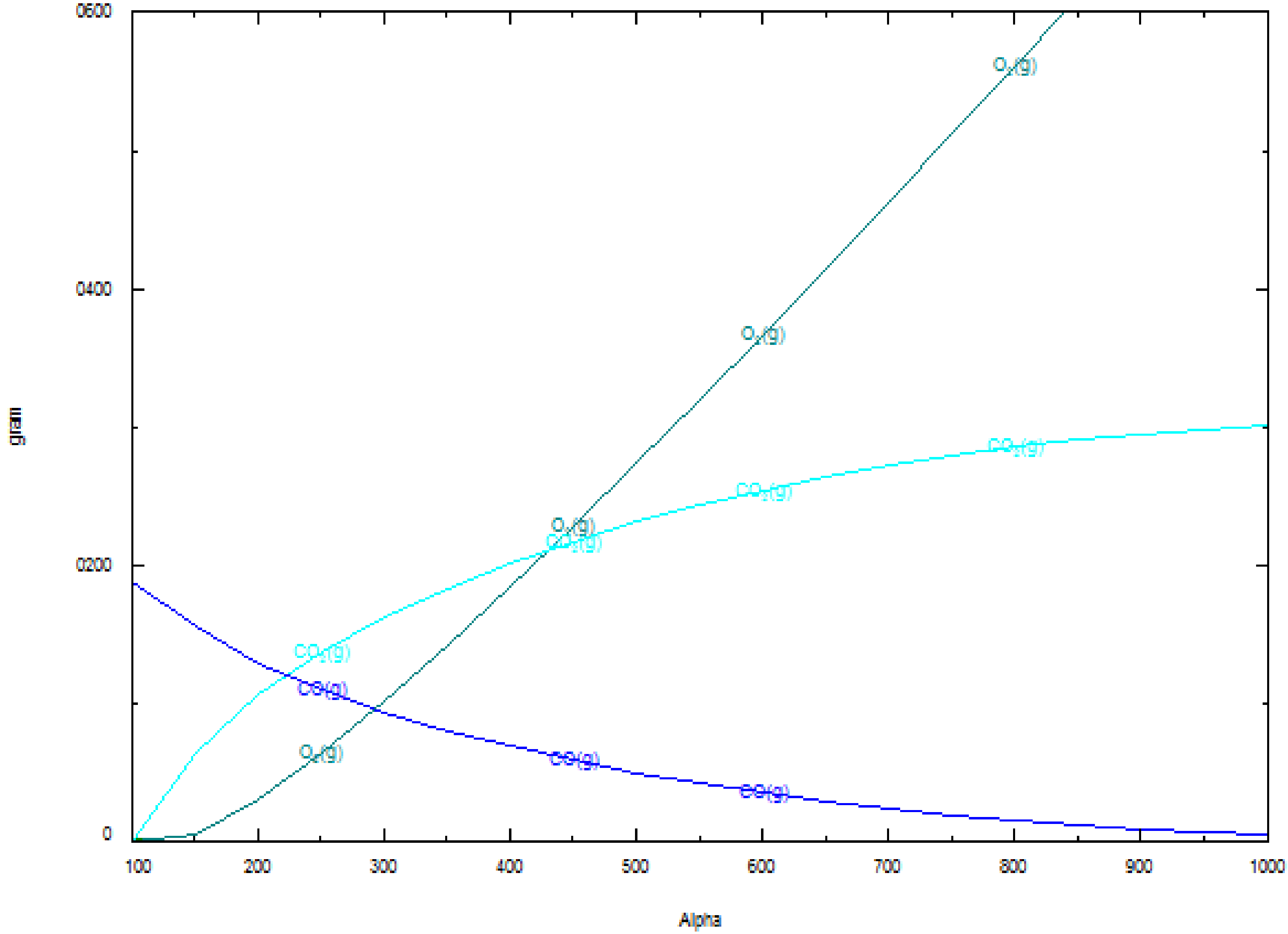
Subbituminous Coal

Gas Composition



Anthracite Coal

Gas Compostion



Design and Conclusions

- After a preliminary investigation into the use of different coal and gas mixture content, it is evident that the Anthracite coal gives the cleanest and most efficient burn.
- It is consistent with the theory that this coal has the highest energy value.
- Also, the slag and the gases are comparably lower than those found with the other coals.

THANK YOU!